Real-Time Prediction of Tropical Cyclone Intensity Using COAMPS-TC

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Introduction: The demand for more accurate tropical cyclone (TC) forecasts with longer lead times is greater than ever due to the enormous economic and societal impact of these storms. There has been spectacular improvement in TC track prediction; a three-day hurricane track forecast today is as skillful as a one-day forecast was just 30 years ago. However, there has been little progress in improving TC intensity and structure forecasts due to a variety of reasons, ranging from a lack of critical observations under high wind conditions and in the TC environment, to inaccurate representations of TC physical processes in numerical weather prediction (NWP) models. Advances in high-resolution TC modeling and data assimilation are thought to be necessary to significantly improve the performance of intensity and structure prediction. To this end, the Naval Research Laboratory in Monterey, California, has developed the Coupled Ocean/Atmosphere Mesoscale Prediction System for Tropical Cyclones (COAMPS-TC™), a new version of COAMPS® designed specifically for high-resolution tropical cyclone prediction.

COAMPS-TC System: The COAMPS-TC system is comprised of data quality control, analysis, initialization, and forecast model subcomponents. A TC version of the Navy Atmospheric Variational Data Assimilation System (NAVDAS) has been developed to blend the available atmospheric observations from a plethora of sources, along with synthetic observations that define the TC structure and intensity. The COAMPS-TC atmospheric model uses the nonhydrostatic and compressible form of the dynamical equations; and includes physical parameterizations of cloud microphysical processes, convection, radiation, boundary layer processes, and surface layer fluxes.[1] The COAMPS-TC system allows for moving nested grid families that independently follow individual tropical cyclone centers. The COAMPS-TC system has the capability to operate in a fully coupled air–sea interaction mode using the Navy Coastal Ocean Model (NCOM) and the Simulating WAves Nearshore (SWAN) model.[2] The Navy Coupled Ocean Data Assimilation (NCODA) system is used to initialize the ocean.

Real-Time Demonstration of COAMPS-TC: Real-time COAMPS-TC forecasts have been conducted using U.S. Department of Defense High Performance Computing (HPC) platforms over the past several years. An example of the intensity forecast performance of COAMPS-TC for a large number of cases (more than 450 cases at the 24 h forecast time) in the W. Atlantic region for the 2010 and 2011 seasons is shown in Fig. 1 (homogeneous statistical sample). The COAMPS-TC model had the lowest intensity error of any dynamical model for the 36 to 120 h forecast times, which is an important period for forecasters and decision makers. Other numerical models included in this analysis are operational models run by NOAA (HWRF, GFDL), and the Navy's current operational limited area model (GFDN).

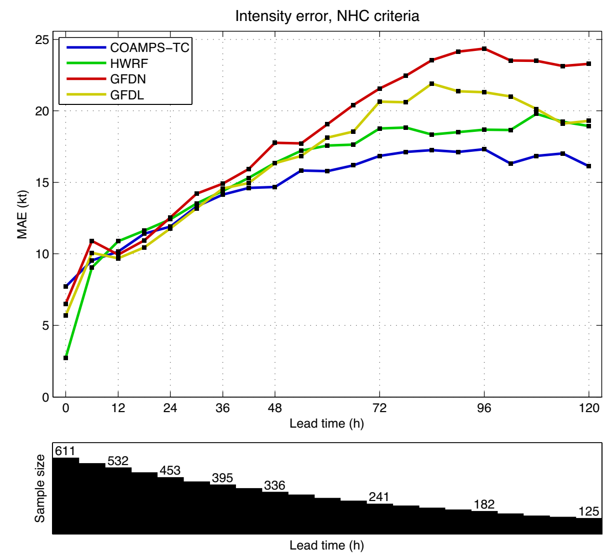

FIGURE 1
Wind speed mean absolute error (MAE) (knots; 1 knot = 0.514 m s^{-1}) as a function of forecast time for the 2010 and 2011 seasons in the Atlantic basin for a homogeneous statistical sample. The numerical models included in this analysis are the Navy's COAMPS-TC, operational models run by NOAA (HWRF, GFDL), and the Navy's current operational limited area model (GFDN). The number of cases is shown at the bottom. (NHC = National Hurricane Center).

An example of a real-time COAMPS-TC forecast for Hurricane Irene (2011) is shown in Fig. 2. The composite National Weather Service (NWS) radar reflectivity (a proxy for the rainfall distribution and intensity) is shown in the top panel near the time of landfall in North Carolina at 1148 UTC 27 August 2011, and the COAMPS-TC predicted radar reflectivity at 36 h valid at 1200 UTC is shown in the bottom panel. The COAMPS-TC forecast shown in Fig. 2 is for the model second grid mesh (15 km horizontal resolution). The model prediction was accurate in the track, eventual landfall location, and storm intensity, as well as the

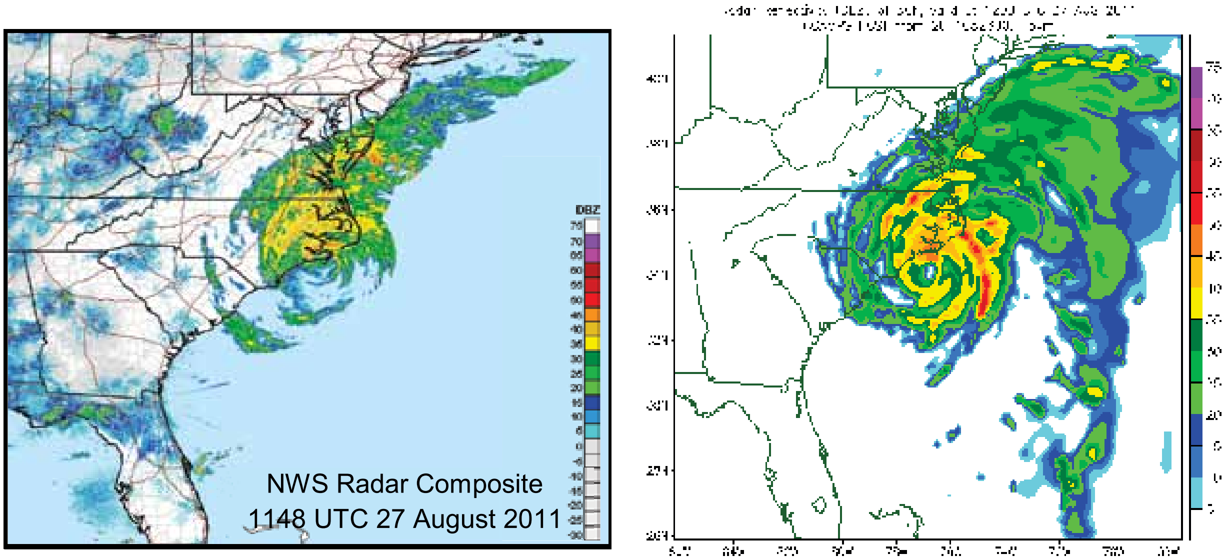

FIGURE 2
The NWS composite radar reflectivity valid at 1148 UTC 27 August 2011 (left panel) (source NOAA) and the COAMPS-TC 36 h forecast radar reflectivity performed in real time and valid at 1200 UTC 27 August (right panel) for Hurricane Irene. The COAMPS-TC reflectivity is shown for the second grid mesh, which has a horizontal resolution of 15 km.

structure and size, especially important characteristics of this particular storm in such close proximity to the U.S. East Coast. The COAMPS-TC prediction captures the large areal extent of the precipitation field, as well as its asymmetry about the TC center (most of the precipitation is north and east of the center). This large shield of heavy precipitation caused severe river flooding as it slowly moved north through the mid-Atlantic and northeast United States. Overall, the Navy's COAMPS-TC real-time intensity predictions of Hurricane Irene outperformed other leading operational governmental forecast models, as shown in Fig. 3. All the available models except COAMPS-TC had a tendency to over-intensify Irene, often by a full storm category or more. These real-time COAMPS-TC forecasts were used by forecasters at the National Hurricane Center (NHC) as part of an experimental NOAA multi-model ensemble. The COAMPS-TC consistently provided accurate real-time intensity forecasts during the period of August 23 through 28, 2011, when critical decisions, including decisions on evacuations, were made by forecasters and emergency managers.

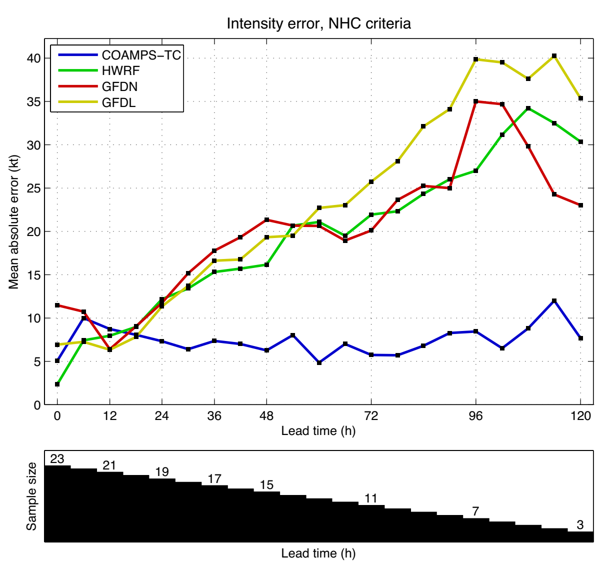

FIGURE 3
Wind speed mean absolute error (MAE) (knots) as a function of forecast time for Hurricane Irene for a homogeneous statistical sample. The numerical models included in this analysis are the Navy's COAMPS-TC, operational models run by NOAA (HWRF, GFDL), and the Navy's current operational limited area model (GFDN). The number of cases is shown at the bottom. Only forecasts after Irene has moved away from Hispaniola are shown here.

Prediction of tropical cyclone track and particularly intensity remains one of the greatest challenges in meteorology today. The results of this research highlight the promising capability of COAMPS-TC. While COAMPS-TC accurately predicted the evolution of Irene and other tropical cyclones in real time, it has not predicted all TCs equally well. The data collected during the life cycle of these storms provide opportunities to study and obtain a greater appreciation of the complex physics and interactions that occur in these systems, and to use this information to improve our COAMPS-TC modeling system.

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computational resources through a grant of Department of Defense High Performance Computing time from the DoD Supercomputing Resource Center at Stennis, MS, and Vicksburg, MS. COAMPS® is a registered trademark of the Naval Research Laboratory.

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[2] S. Chen, T.J. Campbell, H. Jin, S. Gaberšek, R.M. Hodur, and P. Martin, "Effect of Two-Way Air–Sea Coupling in High and Low Wind Speed Regimes," *Mon. Wea. Rev.* **138**, 3579–3602 (2010).

Cirrus Cloud Seeding by Stratospheric Volcanic Aerosol Particles

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Introduction: Lower stratospheric (LS) volcanic incursions can indirectly perturb upper tropospheric (UT) cloud fields (i.e., cirrus clouds) long after the initial eruption cycle from gradual particle settling and re-entrainment back into the troposphere. Volcanic sulfur dioxide and hydrogen sulfide vapor molecules are photo-oxidized in the LS, forming gaseous sulphuric acid, which in turn increases sulfate-based aerosol particle concentrations through nucleation, condensation, and coagulation (i.e., hydrated sulfuric acid solution droplets). These particles, combined with any embedded silicate ash aloft, are highly efficient ice nuclei.

NRL scientists, in collaboration with colleagues at NASA Goddard Space Flight Center (GSFC), have collected the most compelling observations to date unambiguously linking cirrus cloud seeding to aged stratospheric volcanic particles.[1] The August 7 and 8, 2008, Mt. Kasatochi eruption injected gases and ash into the LS over the Aleutian Islands of southwestern Alaska, nearing 17.0 km (all heights above mean sea level). Ten days downwind over south-central Maryland, Kasatochi aerosols were profiled by ground-based lidar mixing into the UT near a tropopause fold. Driven by enhanced ambient water vapor concentrations, cirrus clouds and ice crystal fallstreaks emerged from within the volcanic layer, likely induced by either homogeneous freezing of sulfate solution droplets or their heterogeneous activation by ash. NASA and NOAA satellite observations add contextual evidence supporting these findings.

Kasatochi Particles and Cirrus Cloud Seeding over Maryland: On August 17 and 18, or just a week after the Kasatochi eruption, LS aerosol particles were profiled in zenith-oriented 0.532 μm lidar measurements collected at the NASA Micropulse Lidar Network (MPLNET) field site on the GSFC campus in Greenbelt, Maryland (Fig. 4). Lidar backscatter is proportional to particle number concentration and cross-sectional area. The LS layer depicted in Fig. 4 thus represents scattering by newly formed sulfate solution droplets and any ash debris aloft. The cold-point tropopause height measured at nearby Sterling, Virginia, during this period varied between 12.0 and 12.5 km.

Hyperspectral ultraviolet composite retrievals of sulfur dioxide concentration over the eastern United States at 1815 UTC on the 17th shown in Fig. 5(a), derived from NASA Ozone Monitoring Instrument (OMI) measurements, depict transient Kasatochi LS filaments approaching central Maryland. Regional water vapor imagery collected concurrently from a NOAA geostationary satellite (6.47 to 7.02 μm broadband channel) is shown in Fig. 5(b). Subsidence associated with a tropopause fold, marking the intrusion of stable stratospheric air into the baroclinic region beneath the jet stream propagating along the base of a geopotential height trough apparent over the east-central United States, is interpreted from a relatively dark band stretching from Nebraska to Maryland. Tropopause folds are turbulent, thus inducing UT/LS exchange.

Beginning 2000 UTC on the 17th, with maximum SO_2 concentrations reaching the area, increased backscatter was measured with the MPLNET instrument above 13.0 km, lasting through 0100 on the 18th. Simultaneously, a segment of the layer was displaced downward into the UT, reaching below 11.0 km by 0500. From 2200 until 0400, strong and transmissive signals characteristic of cirrus clouds and ice crystal fallstreaks were profiled from 10.0 to 11.5 km, with tops embedded within the UT-entrained layer. A regional true-color composite image derived from NASA Moderate Resolution Infrared Spectroradiometer (MODIS) measurements collected at 1805 UTC on the 17th, in sequence ahead of OMI, is shown in Fig. 6. A relatively narrow band of cirrus clouds and fallstreaks, corresponding with those profiled by the MPL, were oriented from northwestern Virginia across the Chesapeake Bay and extending northeastward over the western Atlantic.

Two scenarios for cirrus cloud seeding likely reconcile this event. First, regional temperatures above 10.0 km were colder than 235 K, or the approximate threshold for homogeneous freezing of water that in solution is believed a function of water activity as opposed to

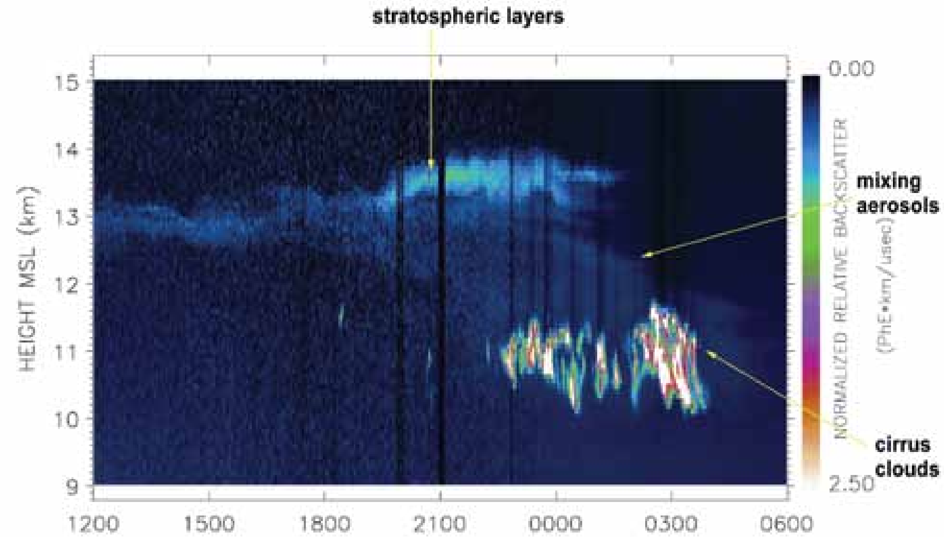

FIGURE 4
NASA Micropulse Lidar Network zenith measurements of normalized relative backscatter signal for 1200 to 0600 UTC 17 to 18 August 2008 from 9.0 to 15.0 km collected at the Greenbelt, Maryland, site on the campus of Goddard Space Flight Center.

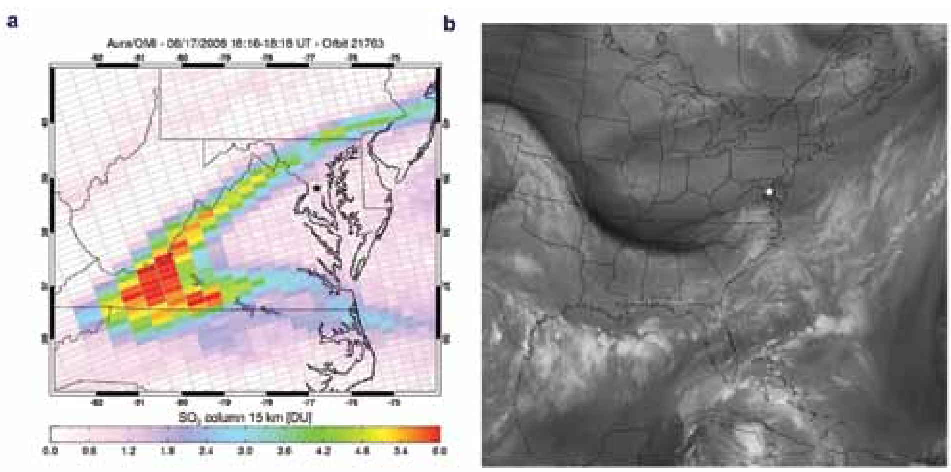

FIGURE 5
(a) NASA Ozone Monitoring Instrument composite measurements of SO_2 concentration (reported in Dobson Units, where 1 DU = 2.69 × 10^{16} molecules/cm^2) over the eastern U.S. collected at 1815 UTC 17 August 2008. (b) Corresponding NOAA GOES water vapor imagery for the region concurrently at 1815 UTC. A star (★) is used to denote the approximate location of the MPLNET ground site in each image.

any relation to the nature of the solute itself. In this scenario, the preferential freezing of the larger sulfate solution droplets at higher temperatures occurs versus smaller ones in equal dilution due to the stochastic nature of homogeneous nucleation and proportionality of freezing rate with droplet volume. Hygroscopic growth in relatively moist UT air and the subsequent freezing of larger sulfate solution droplets would proceed, with growth sustained by vapor deposition governed by ambient ice supersaturation.

Heterogeneous droplet activation through sulfate solution droplet interaction with silicate ash debris is a second potential mechanism. In this scenario, nucleation and ice crystal growth are relatively fast and thus constrained to low ice number densities. The reverse is found, and ice number densities are higher, when droplets freeze homogeneously. In Figs. 4 and 6, many of the cells appear opaque, implying that ice number densities were not unusually low within some of the clouds, a finding that would support homogeneous freezing. However, sheared fallstreaks with no parent heads are similarly apparent in the available MPLNET/MODIS data, suggesting likely low number densities and implying that perhaps heterogeneous nucleation by ash had occurred. It is plausible that both mechanisms were occurring simultaneously.

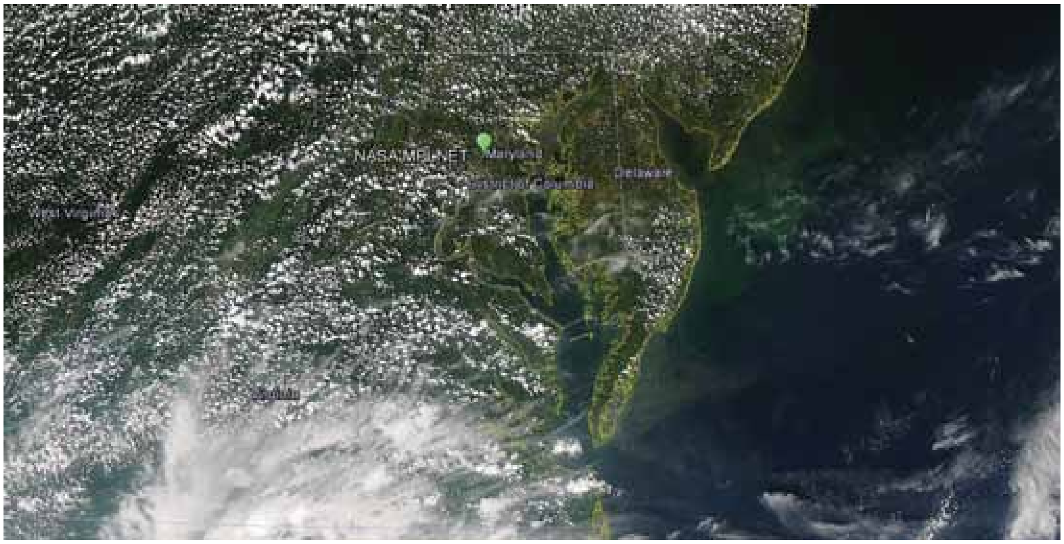

FIGURE 6
NASA Moderate Resolution Infrared Spectroradiometer true-color composite centered over Maryland collected at 1805 UTC 17 August 2008, with the MPLNET ground site labeled.

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[Sponsored by ONR]

Reference

[1] J.R. Campbell, E.J. Welton, N.A. Krotkov, S.A. Stewart, and M.D. Fromm, "Likely Seeding of Cirrus Clouds by Stratospheric Kasatochi Volcanic Aerosol Particles Near a Mid-Latitude Tropopause Fold," *Atmos. Env.* **46**, 441–448 (2012), doi:10.1016/j.atmosenv.2011.09.027.

Merging Geographic Information Systems Technologies with Environmental Prediction

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Synopsis: The Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS®) – On-Demand System (COAMPS-OS®) is software developed at NRL that the U.S. Navy uses to run the COAMPS operational mesoscale numerical weather prediction system. In 2011, NRL released the first version of the COAMPS-OS Dashboard Viewer (CDV) into operations at the U.S. Navy's Fleet Numerical Meteorology and Oceanography Center (FNMOC). The CDV is a Geographic Information Systems (GIS) web browser application for creating, viewing, and exporting all COAMPS model visualizations and most products provided by COAMPS-OS.

Rationale: Current technologies used by operational naval forecasters range from static images with zero interaction, to a highly interactive "thick" client, namely, the Joint METOC (Meteorology and Oceanography) Viewer (JMV). While static images are relatively easy to generate and deliver to the user, forecasters have very little, if any, customization options, and searching for and finding products can be cumbersome, as they are often buried behind many web pages, portals, and links. While JMV is the tool of choice for the shipboard forecaster by providing access to countless products and many tools, the drawback is that it must first be installed on a user's system and is generally limited to meteorological and oceanographical products. Scientists also have limited options for performing necessary model verification within COAMPS-OS. Currently, scientists use static images, similar to naval forecasters, accompanied by statistics from static web pages, with no option to overlay or fuse the products together for a better analysis. It was therefore necessary to provide COAMPS-OS users with an easily accessible and highly interactive web application that allows them to easily explore, visualize, combine, and export weather products using the latest technologies.

The Application: The CDV client and server uses open source technologies that leverage the power of many developers and users around the world to bring the best and latest features to military operators and scientists. The CDV client is built using the Google Web Toolkit (GWT) development framework, which enables NRL scientists to develop a complex web application in the Java programming language, and then convert it into an Asynchronous JavaScript and XML (AJAX) web application. The AJAX application produced by GWT is optimized for all major web browsers (Fig. 7), allowing the CDV to reach many users regardless of the platform. Using AJAX, no installation on a user's computer is needed; all that is needed for a user to launch and use the CDV is a web browser with an Internet connection.

The heart of the CDV client is its GIS web map. The CDV web map uses the OpenLayers open source software package, which provides an interactive web map similar to Google Maps®. Use of a technology that most people are already familiar with in their daily lives helps keep the CDV's learning curve low. The current operational version of the CDV web map displays products includes more than 60 COAMPS forecast products and ocean products from the Navy Coastal Ocean Model (NCOM) and WAVEWATCH III® (WW3) models. This type of data integration is unprecedented in COAMPS-OS. The CDV also has the ability to display remote sensing data from radar and satellite sources. For scientists, the CDV can display model verification data provided by COAMPS-OS with the actual COAMPS forecast products, providing a rich model forecast verification tool. The CDV client and server can also communicate with other GIS clients and servers to provide a powerful GIS integration tool (Fig. 8). For example, other WMS supporting applications, such as ArcGIS Explorer®, can communicate with the CDV server and display COAMPS-OS data on its map interface. For military operators, any geospatial intelligence information exposed as a standard WMS service can be viewed by the CDV, enhancing their environmental situational awareness.

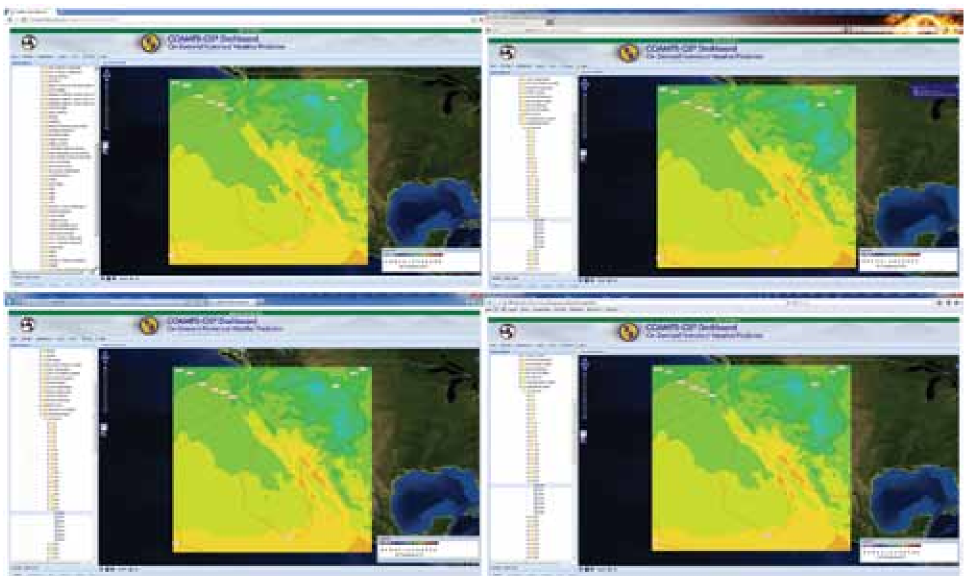

FIGURE 7
A mosaic of the CDV client in four popular web browsers: Google Chrome (top left), Mozilla Firefox (top right), Microsoft Internet Explorer 9 (bottom left), and Apple Safari (bottom right). The data displayed is COAMPS surface air temperature with 500 millibar geopotential height contours.

using standard protocols and services such as the Web Map Service (WMS).

The CDV server provides the CDV client with the necessary web services to explore, visualize, and export COAMPS-OS products. The raw weather and ocean model data are converted on the server into standard GIS formats to be consumed by the CDV client as well as other GIS clients.

Integration and Features: Using standard GIS formats and protocols, the CDV client is able to display data from a variety of sources simultaneously. This

Perhaps one of the best features of the CDV system is its ability to create a product from a variety of source datasets in any way the user desires and export it into three common formats: PNG image, Shapefile, and Keyhole Markup Language (KML). By far the most popular format of the three is KML, the file format of choice in Google Earth®. Never before in COAMPS-OS has a user had the ability to create his own product and view, integrate, and interact with it on the 3D Google Earth globe (Fig. 9).

The CDV is continuing to undergo development at NRL in order to provide U.S. military operators with more features, increased usability, and better access to meteorological and other geospatial intelligence information.

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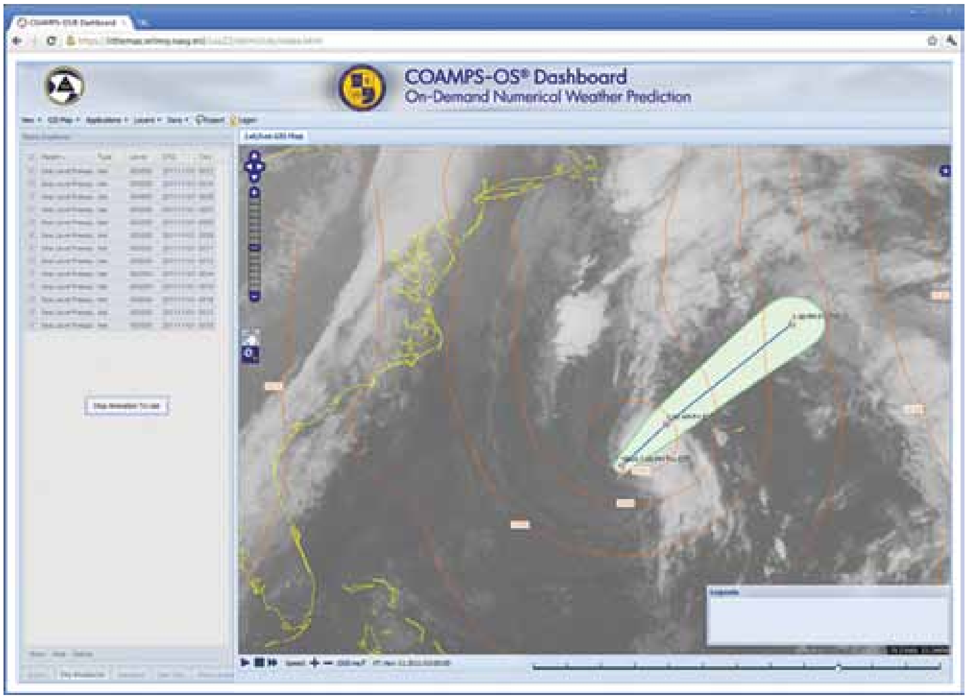

FIGURE 8
Infrared satellite imagery and National Hurricane Center (NHC) forecast of an Atlantic tropical system integrated with COAMPS forecasted sea level pressure. NHC and satellite data were provided by the National Oceanic and Atmospheric Administration's National Ocean Service nowCOAST WMS service.

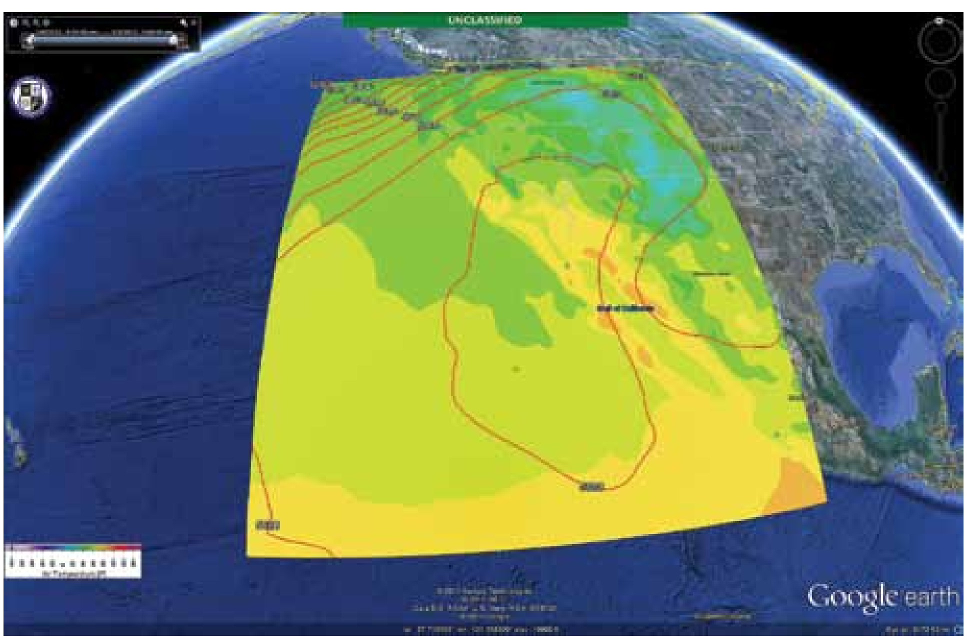

FIGURE 9
Same meteorological data from Fig. 7 exported to KML using the CDV and displayed in Google Earth.